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Total focusing method with correlation processing of antenna array signals

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Abstract. The article proposes a method of preliminary correlation processing of a complete set of antenna array signals used in the image reconstruction algorithm. The results of experimental studies of 3D reconstruction of various reflectors using and without correlation processing are presented in the article. Software 'IDealSystem3D' by IDeal-Technologies was used for experiments. Copper wires of different diameters located in a water bath were used as a reflector. The use of correlation processing makes it possible to obtain more accurate reconstruction of the image of the reflectors and to increase the signal-to-noise ratio. The experimental results were processed using an original program. This program allows varying the parameters of the antenna array and sampling frequency.

1. Introduction

Synthetic aperture focusing technique (SAFT) was proposed for radar systems in the 50s of the last century. Practical use of the method began with the advent of digital computers in the late 80's [1-3], and more advanced methods, such as a total focusing method (TFM) [4], a common source method (CSM) [5], were introduced in the mid-nineties.

The TFM has a high spatial resolution of the ultrasound image and allows accurate predicting and evaluating the position and size of defects. Despite this, in the beginning, this method was not widely used in the field of nondestructive testing because of the large amount of numerical computations and long processing, especially when a control result is to be displayed in 3D. Currently, with the help of modern computer technology, the TFM is widely used to reconstruct the objects of control in the form of two-dimensional and three-dimensional pictures [6-11]. The TFM algorithm can be implemented in the time or frequency domain [12]. This article presents the results of applying the TFM method in the time domain for a three-dimensional reconstruction of inspection objects. The experiments were carried out using software 'IDealSystem3D' by IDeal-Technologies. The copper wires of different diameters located in a water bath were used as reflectors.

The purpose of the study is to determine the resolution of the total focusing method, supplemented by correlation processing and 3D displaying of control results.

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2. An algorithm of three-dimensional reconstruction in the time domain using TFM

The ultrasonic wave propagates in an inhomogeneous medium and is reflected from the boundary between two different materials. In acoustic imaging systems using the echo-pulse approach, the transmitter radiates a short pulse of ultrasonic energy, and the receiver receives an echo, which is then used to reconstruct the image of the internal structure of the object.

When applying the TFM in the time domain for the three-dimensional reconstruction of the inspection object, the space of the inspection object under the transducers is divided into finite elements (pixels). All echoes received from all possible transmitter-receiver array combinations are taken into account when calculating the signal amplitude in each pixel [10].

In this paper, a multi-element linear array and TFM are used to focus each point of the control zone during post-processing of the original data. The method is based on the alternate excitation of each transceiver in an array with a broad beam pattern. Reception of reflected signals is carried out by all transceiver simultaneously. A matrix of temporary data is formed, which is then used to obtain the image [14]. When scanning, an array moves along two perpendicular axes with a predetermined pitch above the inspection object in the water bath.

For an element with x, y, z coordinates, the acoustic image is calculated as follows [14]:

$$\boldsymbol{A}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}) = \sum_{\boldsymbol{b}=\mathbf{1}}^{\boldsymbol{n}} \sum_{\boldsymbol{c}=\mathbf{1}}^{\boldsymbol{n}} \left|\boldsymbol{P}_{\boldsymbol{b},\boldsymbol{c}}\,(\boldsymbol{t}_{\boldsymbol{b}\mathrm{c}})\right|,$$

where b and c are the numbers of the receiving and transmitting piezoelectric transducers, $\boldsymbol{t}_{\boldsymbol{b}\mathrm{c}}$ is the propagation time of the signal from transducer *b* to the pixel and back to transducer *c*.

The value $\boldsymbol{A}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$ gives the transparency of the image in coordinate space x, y, z. High-frequency echoes $\boldsymbol{P}_{\boldsymbol{b},\boldsymbol{c}}\,(\boldsymbol{t}_{\boldsymbol{b}\mathrm{c}})$ are summed up. Index ‘b, c’ here indicates a pair of transducers (transmitter-receiver) from which an echo is received. The timing of echo $\boldsymbol{t}_{\boldsymbol{b}\mathrm{c}}$ is compared with the pixel which coordinates are [x, y, z] (Figure 1), having the geometric arrangement of ultrasonic transducers [15, 16]:

$$\boldsymbol{t}_{\boldsymbol{b}\mathrm{c}} = \frac{(\boldsymbol{r}_{\boldsymbol{b}}+\boldsymbol{r}_{\boldsymbol{c}})}{\boldsymbol{C}_{\boldsymbol{l}}},$$

where $\boldsymbol{r}_{\boldsymbol{b}}$ is the distance from the transmitter with the number ‘b’ to the pixel in which the amplitude is determined; $\boldsymbol{r}_{\boldsymbol{c}}$ is the distance from the receiver with the number ’c’ to the same pixel; $\boldsymbol{C}_{\boldsymbol{l}}$ is the velocity of the longitudinal waves.

The distances from the pixel to the receiver and the emitter in the three-dimensional coordinate system are determined using the expressions:

$$\boldsymbol{r}_{\boldsymbol{b}} = \sqrt{(\boldsymbol{x}_{\boldsymbol{b}}-\boldsymbol{x})^2+(\boldsymbol{y}_{\boldsymbol{b}}-\boldsymbol{y})^2+\boldsymbol{Z}^{\mathbf{2}}},\ \boldsymbol{r}_{\boldsymbol{c}} = \sqrt{(\boldsymbol{x}_{\boldsymbol{c}}-\boldsymbol{x})^2+(\boldsymbol{y}_{\boldsymbol{c}}-\boldsymbol{y})^2+\boldsymbol{Z}^{\mathbf{2}}},$$

where x, y, z are the pixel coordinates; $\boldsymbol{x}_{\boldsymbol{b}}$, $\boldsymbol{y}_{\boldsymbol{b}}$ are the transmitter coordinates; $\boldsymbol{x}_{\mathrm{c}}$, $\boldsymbol{y}_{\mathrm{c}}$ are the receiver coordinates.

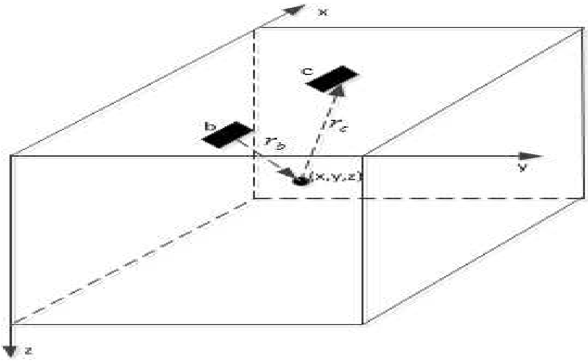


Figure 1. A scheme of the location of the acoustic array at the inspection object

To obtain a 3D reconstruction of the image, the following algorithm was implemented:
- Partition of the space under the antenna array into M pixels with a given pitch.
- Calculation of the amplitude of signal for each pixel M of the control zone taking into account all positions of the antenna array.
- Summation of all obtained results by the formula:

$$A_M(x,y,z) = \sum_{i=1}^{n} A_i(x,y,z).$$

- Coding of the result with the color gamut.
- Image constructing.

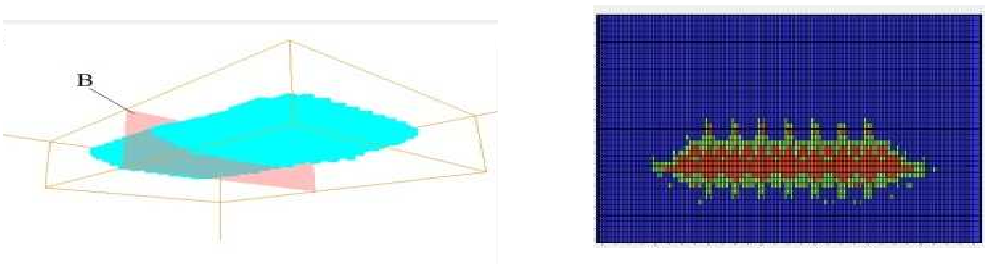
To improve image quality, it has been proposed to apply the correlation function [18]:

$$A_M(x,y,z) = \sum_{i \# j} A_i(x,y,z) \cdot A_j(x,y,z).$$

The TFM resolution depends on the duration of the acoustic pulse, the dimensions of the antenna array, and the speed of ultrasound. The limiting resolution is half of the length of the acoustic waves [3].

3. Experimental results

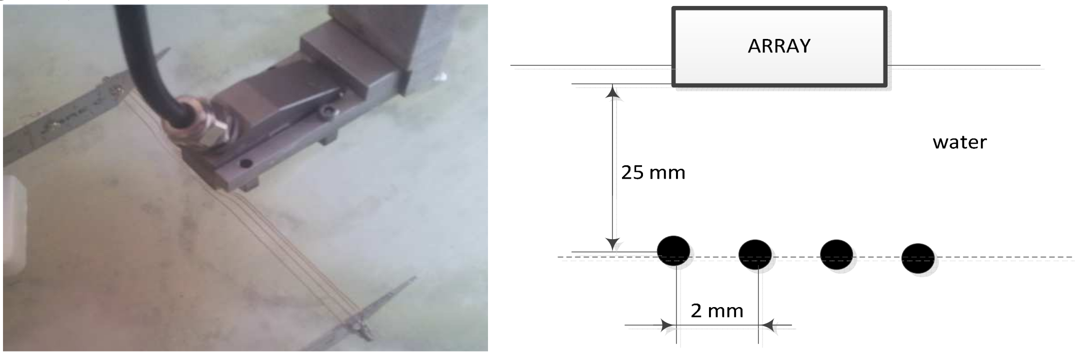
The experiments were carried out using a linear antenna array of 16 elements. The distance between the elements was 0.6 mm. The resonant excitation frequency of the transducer elements was 5 MHz and the sampling frequency was 80 MHz. The ultrasound velocity in water was assumed to be 1500 m/s (the wavelength is 0.3 mm, respectively). Processing experimental results was carried out in original program written in Delphi with the use of OpenGL library. This program automatically processes data and constructs a 3D image of the object (Figure 2a) and section (B) of the object (Figure 2b). Also, the program allows changing the viewing angle and the plane of a tomographic image.



a) b)

Figure 2. Results of modelling: a) 3D image of the object, b) section (B) of the object

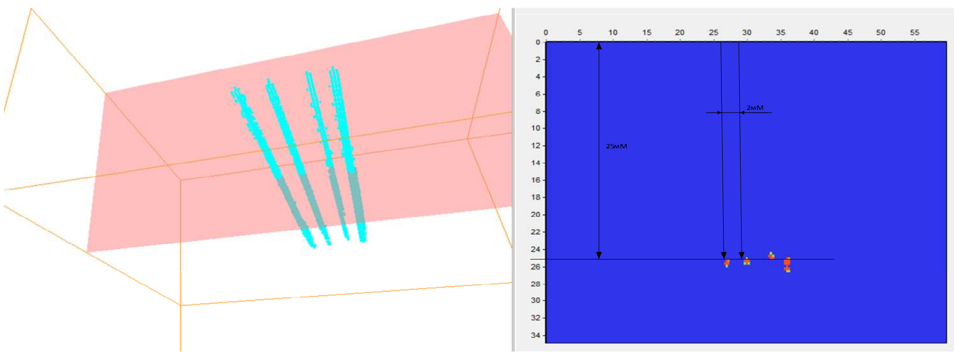
In the first experiment, the TFM resolution was investigated. For this purpose, reflectors were made in the form of 4 parallel copper wires with a diameter of 0.3 mm located at a distance of 2 mm from each other. Reflectors were placed in a water bath at a depth of 25 mm from the array surface (Figure 3).



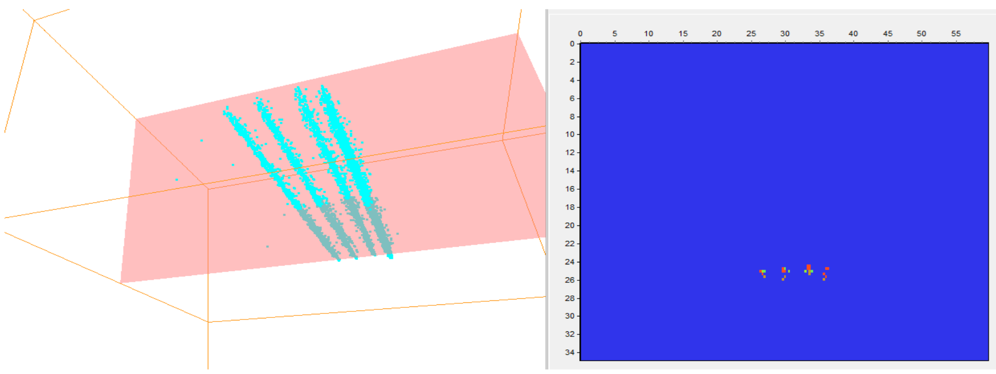
a) b)

Figure 3. A photo of the sensor and reflectors (a); a scheme of the relative position of the reflectors and the sensor in a bath (b)

A 3D image of the reflectors and their tomographic section are shown in Figure 4.



a)

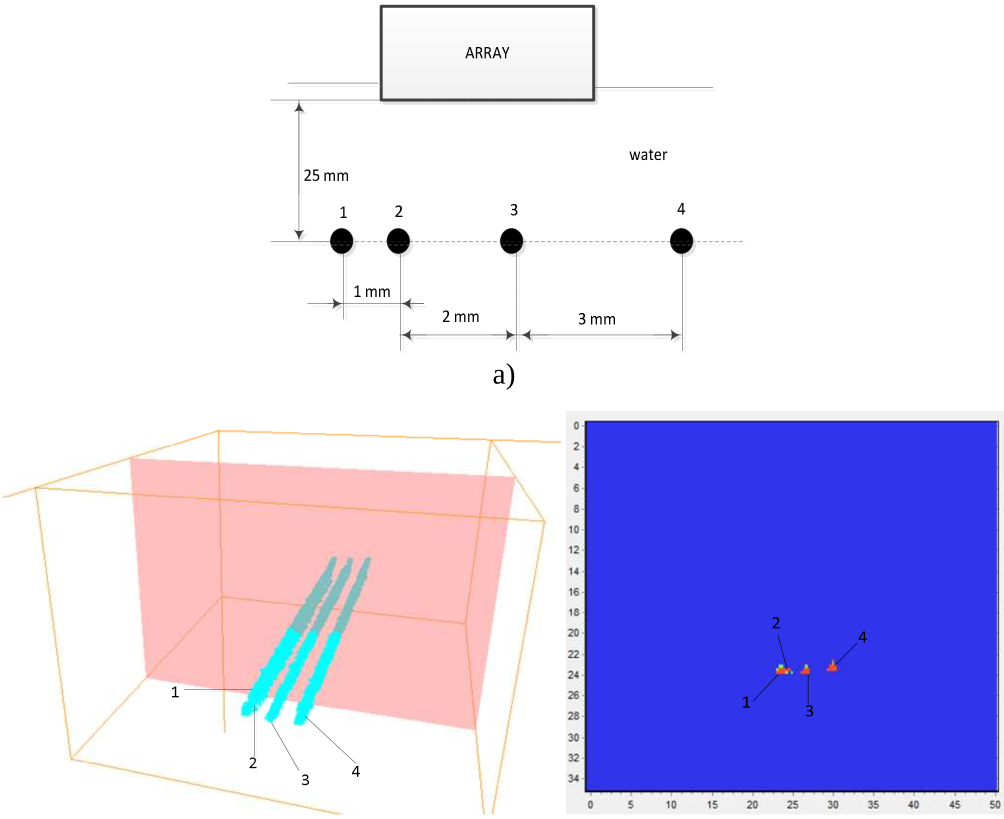


b)

Figure 4. A 3D model of reflectors' image and their tomographic section*:*
a) with the use of correlation function; b) without correlation function.

Figure 4 shows that 3D model of the reflectors image obtained with the use of correlation function is more precise than the one obtained without the correlation function. This indicates an improvement in the signal-to-noise ratio when applying the correlation function. And the tomographic section shows a more accurate distance between the reflectors and the range at which they are located.

In the second experiment, the reflectors made of 4 copper wires of 0.45 mm diameter located at a distance of 1, 2 and 3 mm from each other were used. Reflectors were placed in a water bath at a depth of 25 mm from the surface of the antenna array (Figure 5a). A 3D image of the reflectors is shown in Figure 5b, and their tomographic image in Figure 5c. The reconstruction of the image of the reflectors was carried out using the correlation function.

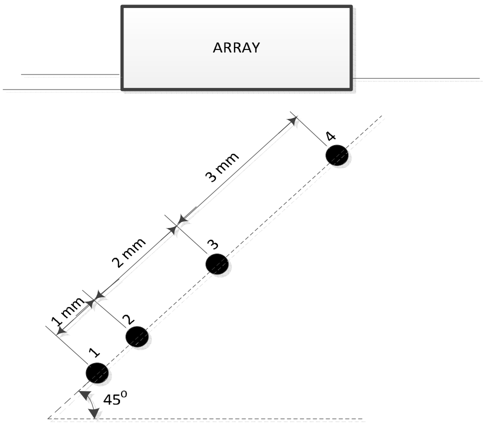


b) c)

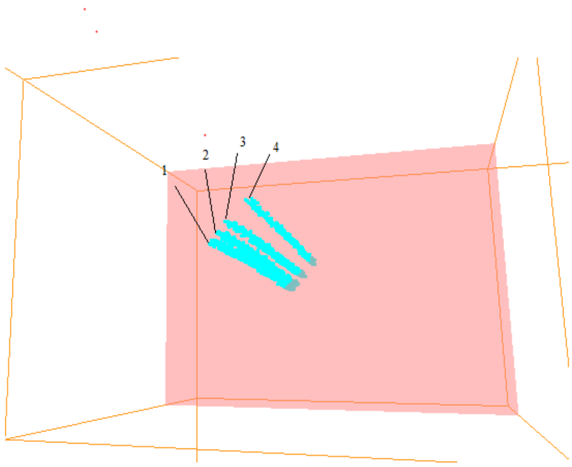
Figure 5. The location of the reflectors in the inspection object (a), 3D image of the reflectors (b) and their tomographic image (c). 1..4 are the numbers of reflectors

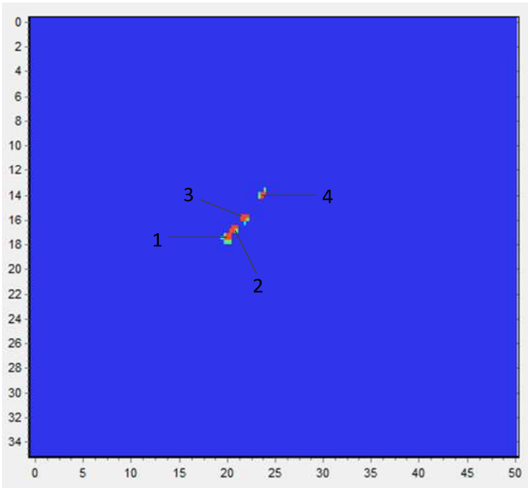
Analysis of the reconstructed image of the reflectors shows that the reflectors located at a distance of 1 mm from each other (first and second) are not distinguished when using TFM and are displayed as one reflector with enlarged dimensions relatively to the other two reflectors (third and fourth).

In the third experiment, the reflectors used in the second experiment were installed on an inclined plane at an angle of 45 degrees to the horizon (Figure 6a). Three-dimensional reconstruction of the image of reflectors in the bath is shown in Figure 6b. Figure 6c shows their tomographic image.



a)





b) c)

Figure 6. The location of the reflectors in the inspection object (a), the three-dimensional image of the reflectors (b) and their tomographic image (c). 1..4 are numbers of reflectors

As in the previous case, the correlation function was used for the three-dimensional reconstruction of the reflectors. Figure 6 shows that the first and second reflectors are displayed as a single reflector. The third and fourth reflectors are displayed separately.

4. Conclusion

From the conducted research, it is possible to draw a conclusion that the algorithm and the program created on the basis of the TFM with correlation processing of signals allows one to reconstruct the 3D image of reflectors in the inspection object, to obtain tomographic sections. The program allows determining not only the position of defects, but also its shape and dimensions. The use of correlation processing made it possible to increase the signal-to-noise ratio, to obtain a sharper image of the reflectors, but the resolution remained changeless.

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References

[1] Elgarem A 1989 Multidepth synthetic aperture processing of ultrasonic data *IEEE Transactions on* Ultrasonics, *Ferroelectrics, and Frequency Control* **36(3)** 384 – 385
[2] Karaman M, Li P C, O'Donnell M 1995 Synthetic Aperture Imaging for Small Scale Systems *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **42(3)** 429-442
[3] Chiao R Y, Thomas L J 1994 Analytical evaluation of sampled aperture ultrasonic imaging techniques for NDE *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* **41(4)** 484-493
[4] Thomenius K 1996 Evolution of Ultrasound Beamformers, *IEEE Ultrasonics Symposium* **2** 1615-1622
[5] Chiao R Y, Thomas L J 1994 Analytical evaluation of sampled aperture ultrasonic imaging techniques for NDE *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* **41(4)** 484-493
[6] Holmes C, Drinkwater B W, Wilcox P D 2005 Post-processing of the full matrix of ultrasonic transmit-receive array data for non-destructive evaluation *NDT&E International* **38** 701-711
[7] Soldatov A, Soldatov A, Kostina M, Bakanov P, Polonskaya M 2016 Small-angle tomography algorithm for transmission inspection of acoustic linear array *MATEC Web of Conferences 4th Russian Forum for Young Scientists with International Participation "Space Engineering"* ed A Dolgih (EDP Sciences)
[8] Bolotina I, Dyakina M, Kröning M, Mohr F, Reddy K M, Soldatov A, Zhantlessov Y 2013 Ultrasonic arrays for quantitative nondestructive testing an engineering approach *Russian Journal of Nondestructive Testing* **49 (3)** 145-158
[9] Soldatov A I, Makarov V S, Sorokin P V, Kvasnikov K G, Soldatov A A, Selesnev A I, Kroening M 2012 Dynamic imaging acoustic fields in research practice *Proceedings of 2012 7th International Forum on Strategic Technology, IFOST 2012*
[10] Asochakov A S , Shulgina Y V, Soldatov A I, Shulgin E M, Ogorodnikov D N 2016 Method of processing of ultrasonic signal of phased array *Proceedings of International Siberian Conference on Control and Communications* ed O Stukach (Institute of Electrical and Electronics Engineers Inc)
[11] Kvasnikov K G, Soldatov A I, Bolotina I O, Krening K M, Potapenko A A 2013 The use of geometrical acoustics for the solution of visualization problems *Russian Journal of Nondestructive Testing* **49 (11)** 625-630
[12] Lingwall F 2004 Time-domain recontrustion methods for ultrasonic array imaging *PhD Thesis* Uppsala University
[13] Sorokin P V, Soldatov A A, Soldatova M A, Shulgina U V, Abouellail A A 2015 Influence of the echo shapes on the result of tomographic image *Proceedings of International Siberian Conference on Control and Communications* ed O Stukach (Institute of Electrical and Electronics Engineers Inc)
[14] Soldatov A I, Chiglintseva J V 2009 Ultrasonic borehole depth-gauge *Proceedings of International Siberian Conference on Control and Communications* ed O Stukach (Institute of Electrical and Electronics Engineers Inc)
[15] Badalyan V G, Vopilkin A Kh, Dolenko S A, Orlov Yu V, Persiantsev I G 2004 Data-processing algorithms for automatic operation of ultrasonic systems with coherent data processing *Russian Journal of Nondestructive Testing* **12** 791-800
[16] Grigorev A P, Soldatov A I, Sorokin P V 2000 Full-scale simulation system minimization problems Proceedings *of the 6th International Scientific and Practical Conference of Students, Post-Graduates and* Young *Scientists: Modern Techniques and Technology, MTT 2000* ed A Sinebryukhov (Institute of Electrical and Electronics Engineers Inc) pp 97-99
[17] Ifeachor E C, Jervis B W 2002 *Digital signal processing. A practical approach* (Pearson Education Limited)